PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
H01P 7/06, 7/10, H01B 12/02

A1

(11) International Publication Number: WO 98/00881

(43) International Publication Date: 8 January 1998 (08.01.98)

(21) International Application Number: PCT/US97/11164

(22) International Filing Date: 27 June 1997 (27.06.97)

(30) Priority Data:
60/020,766 28 June 1996 (28.06.96) US

(71) Applicant: SUPERCONDUCTING CORE TECHNOLOGIES, INC. [US/US]; 720 Corporate Circle, Golden, CO 80401 (US).

(72) Inventors: MUELLER, Carl, H.; Apartment 2-111, 573 Van Gordon Street, Lakewood, CO 80228 (US). ZHANG, Zhihang; 10139 Garrison Street, Westminster, CO 80021 (US). KOEPF, Gerhard, A.; 700 Kalmia Avenue, Boulder, CO 80304 (US).

(74) Agents: SWARTZ, Douglas, W. et al.; Sheridan Ross P.C., Suite 3500, 1700 Lincoln Street, Denver, CO 80203-4501 (US).

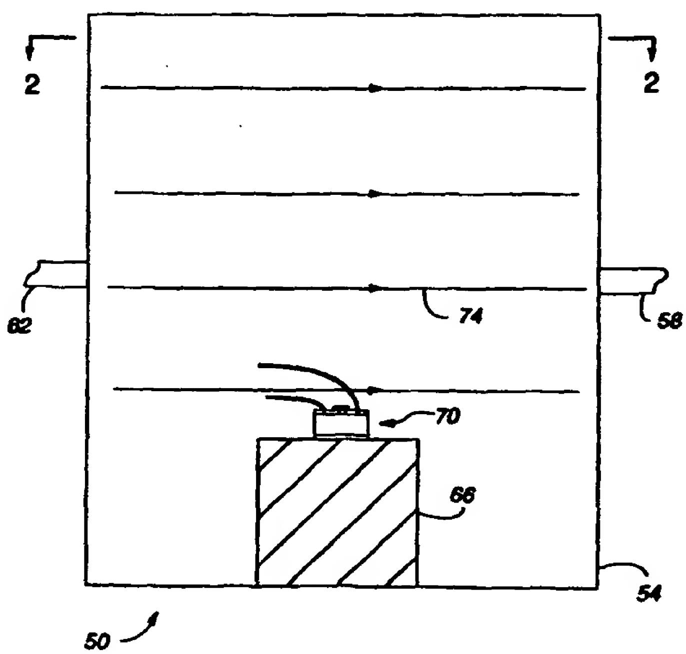
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: NEAR RESONANT CAVITY TUNING DEVICES

(57) Abstract

The present invention pertains to an electronically tunable resonating apparatus (50) which uses a tunable dielectric material (90a, 90b) which is biased by an electric field to alter the resonant frequency in a resonating cavity (54). Electrodes (78, 94) apply the electric field and are connected to a variable voltage source (V), thereby providing a plurality of electric field strengths and thus provides a range of resonant frequencies in resonating apparatus (50). The resonating apparatus (50) is particularly useful for microwave and millimiter wave electromagnetic energy (74).



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania
AM	Armenia
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

NEAR RESONANT CAVITY TUNING DEVICES

FIELD OF THE INVENTION

The present invention relates generally to tunable resonating cavities and particularly to electronically tunable microwave and millimeterwave cavities.

BACKGROUND OF THE INVENTION

Dielectric resonating cavities are components of filters, reflection-type amplifiers, and oscillators. A dielectric resonating cavity refers to a space bounded by an electrically conducting surface in which oscillating electromagnetic energy is stored. Resonating cavities are typically rectangular or cylindrical in shape with conducting side walls and an input and output couple for electromagnetic energy. Dielectric blocks or pucks may be positioned in the cavity to provide a desired resonant frequency of the resonating cavity (i.e., the cavity resonant frequency). The desired cavity resonant frequency determines the frequency characteristics of the electromagnetic energy output by the cavity.

The cavity resonant frequency is determined by the resonant mode and dimensions of the resonating cavity and the electric permittivity of the dielectric block or puck located in the cavity. The cavity resonant frequency can vary in response to thermal expansion/contraction of the resonating cavity, thermally induced fluctuations in the electric permittivity of the dielectric block or puck, and/or dimensional tolerances of the resonating cavity and its placement in the circuit.

One method for fine tuning a cavity in response to fluctuations in the cavity resonant frequency is to use a metal or dielectric material to selectively perturb the electromagnetic energy distribution in the resonating cavity. Typically, this is accomplished either by manually or mechanically turning a number of tuning screws in the cavity or by altering the position or shape of the dielectric block or puck in the cavity. This method can have a slow tuning speed, a low degr e of tuning precision,

and, for mechanical tuning, a high rate of mechanical problems.

Another method for fine tuning a cavity is to alter the permeability of a ferromagnetic or ferrimagnetic material, such as yttrium iron garnet, located in the cavity. The permeability is controlled by controlling the strength of a magnetic field applied to the material. This method can have a slow tuning speed, a high hysteresis loss (especially at frequencies used for cellular and Personal Communications Systems (PCS) wireless system), and a permeability that is strongly dependent upon temperature fluctuations. An additional problem which limits the use of ferrite tuning is that the magnetic field used to tune a first cavity often has an adverse effect on other adjacent cavities located in close proximity to the first cavity.

Yet another method for fine tuning a cavity is to couple a semiconductor varactor to the electromagnetic energy in the cavity. Altering the capacitance of the varactor results in a change in the cavity resonant frequency. Semiconductor varactors are rarely used at microwave or higher frequencies because such varactors can result in a high insertion loss and generate spurious signals at undesired frequencies. In signal transmission applications, the voltage and/or current breakdown strengths of semiconducting varactors can be exceeded when the power level of the cavity exceeds approximately one milliwatt. Filters used for signal transmission typically operate in the 1 to 800 watt range.

Another method for fine tuning a cavity is to alter the capacitance of a varactor diode coupled to the cavity via a coupling loop. The diode capacitance is varied by varying the d.c. voltage applied to the diode, which changes the width of the charge depletion layer in a semiconductor. At microwave and millimeter frequencies, the diode and coupling loop can produce high microwave attenuation due to the series resistance of the

semiconductor areas adjac nt to the charge-depleted portion of the semiconductor. The high attenuation can result in an undesirably low Q, and thus unacceptably high loss of the electromagnetic energy input into the cavity.

SUMMARY OF THE INVENTION

It is an objective of the present invention to provide an apparatus and method for tuning a resonating cavity that provides for a cavity having a high quality factor, especially at microwave or higher frequencies. Related objectives include providing a tuning apparatus that performs effectively at high RF power levels and/or high frequencies, has a relatively low insertion loss, and/or has a relatively high voltage and/or breakdown strength.

It is a further objective to provide an apparatus and method for tuning a resonating cavity that has a relatively high tuning speed. Related objectives include providing a tuning apparatus that is electronically tunable, has a high degree of tuning precision and/or selectivity, has few, if any, moving parts, and is robust and reliable.

These and other objectives are addressed by the tunable electromagnetic resonating apparatus of the present invention. The tunable electromagnetic resonating apparatus includes: (i) a resonating cavity for resonating at a cavity resonant frequency in response to electromagnetic energy received by the resonating cavity; (ii) an input for inputting electromagnetic energy into the resonating cavity; (iii) an output for outputting electromagnetic energy from the resonating cavity; and (iv) an electronically operated tuning device coupled to th resonating cavity. The tuning device includes a dielectric material, located within the resonating cavity, having an electric permittivity that is a function of a variable voltage applied thereto and a biasing device for applying the variable voltage to the dielectric material. To maintain insertion losses low and effectively tune the cavity, the biasing device provides a dielectric

capacitance of no more than about 10 picofarads across the dielectric material. The cavity resonant frequency is varied by varying the dielectric capacitance and thereby altering the electric permittivity. Because the electromagnetic energy is coupled to the tuning device, the cavity resonant frequency is impacted by the variation in the dielectric capacitance.

Relative to existing tuning devices, the tuning device has a number of distinct advantages. The tuning device can be tuned rapidly and with a high degree of precision to a selected cavity resonant frequency. The tuning device can have relatively low insertion losses and therefore the resonating cavity a relatively high Q. The tuning device can perform effectively at high RF power levels and/or high frequencies. The dielectric material can be selected to have a relatively high voltage or breakdown strength. Being electronically actuated, the tuning device has few, if any, moving parts and therefore is robust and reliable.

The electromagnetic energy suitable for the resonating apparatus can have a variety of frequencies. The preferred electromagnetic energy has a frequency that is at least that of microwave energy or a higher frequency. More preferably, the electromagnetic energy is microwave or millimeterwave energy. Microwave energy typically has a frequency ranging from about 300 to about 30,000 MHz. Millimeterwave energy typically has a wavelength ranging from about 10 mm to about 3 mm and a frequency ranging from about 30 to about 100 GHz.

The dielectric material can be any electrically insulating material for which the electric permittivity of the insulating material is altered via application of a voltage, particularly a DC voltage. The dielectric material can be a bulk(i.e., self-supporting or thick film)or thin film ferroelectric or paraelectric material. "Self-supporting bulk dielectric material" refers to a dielectric material having a thickness of at least about 50 microns and preferably no more than about 200 microns and

typically manufactured by sintering, hot pressing, hydrothermal growth, or Czochralski growth techniqu s. Self-supporting dielectric materials are not formed on substrates. "Thick film bulk dielectric material" refers to a dielectric material having a thickness ranging from about 5 to about 100 microns and typically deposited by tape casting or slip casting techniques onto an underlying substrate. "Thin film dielectric material" refers to a dielectric material having a thickness ranging from about 0.01 to about 10 microns and typically deposited by sputtering, laser deposition, sol-gel, or chemical vapor deposition techniques onto an underlying substrate. The selection of a bulk or thin film ferroelectric or paraelectric material for a given application depends upon the cavity resonant frequency and electromagnetic field strength. Generally, the desired characteristics of the ferroelectric or paraelectric material are a high permittivity (e.g., no less than about 1,000) at room temperature, with a low loss tangent (e.g., no more than about 0.02). Preferred ferroelectric and paraelectric materials are crystalline or ceramic materials, including barium strontium titanate, $Ba_xSr_{1-x}TiO_3$, or lead zirconate titanate, $PbZr_{1-x}Ti_xO_3$, where $0 \leq x \leq 1$, and $LaTiO_3$, $PbZrO_3$, $LaZrO_3$, $PbMgO_3$, $PbNbO_3$, $KTaO_3$, and composites and mixtures thereof.

To alter the electric permittivity of the dielectric material, the biasing device applies an electric field to the dielectric material. The preferred strength of the electric field preferably ranges from about 0 to about 500 kv/cm.

To apply the electric field to the dielectric material, the biasing device can include positively charged and negatively charged tuning electrodes in contact with the dielectric material, a power source (e.g., a variable voltage source) which is typically located outside the cavity, and electrical leads extending from the power source to the electrodes which, along with the dielectric

material, are located in the cavity. The electrodes are spaced apart from one another by a gap, thereby forming the dielectric capacitance. In one configuration, the tuning electrodes are located on a common surface of the dielectric material.

The tuning electrodes and dielectric material can be supported by a dielectric substrate having an impedance that is more than the impedance of the dielectric material to cause a greater portion of the electromagnetic energy to pass through the dielectric material than through the dielectric substrate. The dielectric substrate commonly is formed from a material that has a electric permittivity that does not vary with applied voltage, such as lanthanum aluminate ($LaAlO_3$), magnesium oxide (MgO), neodynium gallate ($NdGaO_3$) and aluminum oxide (Al_2O_3).

In a particularly preferred configuration, the tuning electrodes, dielectric material, and dielectric substrate are configured to define a first path for electromagnetic energy through the electrodes and the dielectric material and a second path for electromagnetic energy through the electrodes and the dielectric substrate. The first and second paths are electrically connected in parallel.

To retard losses of electromagnetic energy due to coupling of the energy to the electrical leads, the tuning device can include a leakage control device for controlling the amount of electromagnetic energy conducted by the leads. As will be appreciated, the leads are positioned in the cavity and can therefore couple to the electromagnetic energy. To reduce such coupling, the leakage control device can include a connection between the electrical leads and the tuning electrodes that is located at a voltage node. Alternatively, the leakage control device can include an RF electrical short circuit located along one or both of the leads at a distance of one quarter wavelength of the RF signal from the corresponding voltage node. By way of xample, the RF short circuit can be

formed by a shunt capacitor connected to one or both of the leads.

The location of the tuning device within the cavity depends upon the electromagnetic field distribution and therefore the resonant mode of the cavity. For the $TE_{01\delta}$, $HE_{11\delta}$, and $TM_{01\delta}$ resonant modes, the preferred location of the tuning device (i.e., the tuning electrodes and the dielectric material) is where the electric field portion of the electromagnetic field is greatest (i.e., in close proximity to or on the surface of the dielectric puck or block).

The tuning device can include a transmission line in electrical contact with the tuning electrodes and dielectric material. The tuning device defines a resonant circuit having a resonant frequency. The resonant frequency is altered by altering the electric permittivity of the dielectric material. The tuning device is coupled to the electromagnetic energy in the cavity and the cavity resonant frequency is altered by altering the resonant frequency of the tuning device.

To effectively tune the resonating cavity, a control feedback loop is further provided. The control feedback loop includes: (i) a sensing device for determining the cavity resonant frequency and generating a signal in response thereto; (ii) a variable power source connected to the biasing device for applying power thereto; and (iii) a control device connected to the variable power source for receiving the signal and generating a control signal in response thereto. The variable power source applies power to the biasing device in response to the control signal.

The operation of the control feedback loop involves a number of iterative steps. By way of example, the method includes the iterative steps of: (i) applying a first electric field of a first electric field strength to the dielectric material positioned in the cavity to produce a first electric permittivity in the dielectric material; (ii) measuring a first cavity resonant frequency; (iii)

selecting, based on the first cavity resonant frequency, a second electric field strength that is sufficient to produce a second cavity resonant frequency; and (iv) applying a second electric field of the second electric field strength to the dielectric material. The steps are repeated as many times as necessary to yield the selected cavity resonant frequency. The time required to produce the selected resonant frequency by this method is typically no more than about 1×10^{-3} seconds.

In some applications, the method can include the additional step of comparing the selected cavity resonant frequency with a set of predetermined values for the cavity resonant frequency with corresponding electric field strengths. Based thereon, the control device selects an electric field strength. This step is particularly useful in fully automated tuning systems.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-sectional view along line 1-1 of Figure 2 of an electronically tunable dielectric resonating cavity apparatus according to the present invention;

Figure 2 is a cross-sectional view along line 2-2 of Figure 1;

Figure 3 is a perspective view of a first embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 4 is a top view of an electronically tunable varactor according to a first embodiment of a varactor of the present invention;

Figure 5 is a side view of the varactor of Figure 4;

Figure 6 is a circuit diagram of the electronically tunable dielectric resonating cavity apparatus;

Figure 7 is a perspective view of a second embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 8 is a perspective view of a third embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 9 is a perspective view of a fourth embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 10 is a perspective view of a seventh embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 11 is a top view of an eighth embodiment of a resonant circuit component of the tuning device of the present invention;

Figure 12 is a side view of the component of Figure 11;

Figure 13 is a top view of an electronically tunable varactor according to a second embodiment of a varactor of the present invention;

Figure 14 is a side view of the varactor of Figure 13;

Figure 15 is a top view of an electronically tunable varactor according to a third embodiment of a varactor of the present invention;

Figure 16 is a side view of the varactor of Figure 15;

Figure 17 is a top view of an electronically tunable varactor according to a fourth embodiment of a varactor of the present invention;

Figure 18 is a side view of the varactor of Figure 17;

Figure 19 is a top view of an electronically tunable varactor according to a fifth embodiment of a varactor of the present invention;

Figure 20 is a cross-sectional view of the varactor of Figure 19 taken along line 20-20 of Figure 19;

Figure 21 is a top view of an electronically tunable varactor according to a sixth embodiment of a varactor of the present invention;

Figure 22 is a side view of the varactor of Figure 21;

Figure 23 is a flow schematic of a control feedback loop according to the present invention;

Figure 24 is a plot of cavity tuning as a function of the insertion loss;

Figure 25 is also a plot of cavity tuning as a function of the insertion loss; and

Figure 26 is a plot of cavity-to-tuner sensitivity as a function of the tuner/cavity resonant frequency ratio.

DETAILED DESCRIPTION

Figures 1 and 2 depict an electronically tunable dielectric resonating cavity apparatus of the present invention. The apparatus 50 includes a resonating cavity 54 having an input 58 and output 62 for electromagnetic energy, a dielectric block or puck 66, and a resonant circuit component 70 of an electronic tuning device positioned on or near the puck 66. Although the electric field 74 formed by the electromagnetic energy is depicted for the $TE_{01\delta}$ resonating mode, the apparatus can be tuned effectively for other resonant modes.

The resonant circuit component 70 is depicted in Figure 3. The resonant circuit component 70 is configured as a microstrip line resonator. The component 70 includes a transmission line 78 (i.e., a strip of a conductive material) separated by a gap 82a,b from an end conductor 86a,b on either end of the transmission line 78. "Conductive material" refers not only to normal conductors, such as metals, but also to superconductors, such as YBCO, TBCCO and BSCCO. Dielectric varactors 90a,b are located in each of the gaps 82a,b to load either end of the transmission line 78. A ground plane 94 is located on an opposing side of the substrate 98 from the transmission line 78. The end conductors 86a,b are short circuited to the ground plane 94 by means of via holes 102a,b. Bias lines 106a and b are connected to the transmission line 78 and ground plane 94, respectively, to bias the varactors

90a,b. As will be appreciated, the varactors 90a,b could alternatively be imbedded in the via holes 102a,b.

The width "W_G" of the each of the gaps 82a,b between the transmission line 78 and the end conductors 86a,b is important to realize a high degree of tuning while maintaining insertion losses at an acceptable level. Preferably, the minimum width of the gaps 82a,b is about 2 microns, more preferably about 5 microns, and most preferably about 10 microns, and the maximum width of the gaps 82a,b is about 100 microns, more preferably about 50 microns, and most preferably about 20 microns.

The dielectric varactor 90 is depicted in Figures 4 and 5 for a lumped element configuration. The dielectric varactor 120 includes a self-supporting bulk dielectric material 124 sandwiched between first and second tuning electrodes 128a,b located on opposing sides of the bulk dielectric material 124. The bias lines 106a,b bias the first and second tuning electrodes 128a,b, respectively, and apply a voltage to the electrodes to define the dielectric capacitance between the electrodes 128a,b.

To cause more electromagnetic energy to pass through the dielectric material 124 than the substrate 98, the impedance of the substrate 98 is higher than the impedance of the dielectric material 124. Preferably, the impedance of the substrate 98 is at least about 200% of the impedance of the dielectric material 124. Preferred materials for the substrate 98 include alumina (Al_2O_3), magnesium oxide (MgO), lanthanum aluminate ($LaAlO_3$), and neodynium gallate ($NdGaO_3$).

Figure 6 depicts the RLC circuit diagram for the resonant circuit component 70 when the component 70 is coupled to the electromagnetic energy in the cavity 54. In Figure 6, R_a represents the resistance across the gap 82a; R_b represents the resistance across the gap 82b; C_a represents the dielectric capacitance of the varactor 90a; C_b represents the dielectric capacitance of the varactor 90b; and the inductor L_0 represents the transmission line

78. The resonant frequency of the component 70 is determined by the length of the transmission line 78 and the dielectric capacitance.

While not wishing to be bound by any theory, the variance of the resonant frequency of the component 70 when coupled to the electromagnetic energy in the cavity 54 appears to cause a concomittant change in the cavity resonant frequency and/or phase of the electromagnetic energy in the cavity. Tuning of the component 70 is realized via the voltage-dependent dielectric capacitance of the varactors 90a,b, and the change in the resonant frequency of the component 70 is caused by the change in the dielectric capacitance.

While again not wishing to be bound by any theory, the amount of change in the cavity resonant frequency appears to be directly related to the amount of electromagnetic energy in the cavity 54 that can be coupled into the dielectric material. The minimum mutual coupling coefficient between the component and the electromagnetic energy in the cavity 54 is preferably about 0.002 and more preferably about 0.005 and the maximum mutual coupling coefficient is preferably about 0.05 and more preferably about 0.02. As will be appreciated, the electromagnetic energy in the cavity 54 is most strongly coupled into the dielectric material when the resonant frequency of the component 70 is approximately equal to the cavity resonant frequency. Thus, by altering the resonant frequency of the component 70, the amount of electromagnetic energy coupled into the dielectric material (and therefore the cavity resonant frequency) is altered.

There is a tradeoff between high tunability of the cavity resonant frequency by the tuning device and insertion loss. The resonant frequency of the component 70 must be selected such that the required degree of tuning of the cavity resonant frequency is realized while maintaining the insertion loss below an acceptable limit and the physical size of the component as small as possible. A

high Q component in the tuning device improves the insertion loss of the cavity 54. In light of the tradeoff, the resonant frequency (preferably the first order resonant frequency) is preferably no less than about 65% of the cavity resonant frequency (preferably the first order cavity resonant frequency), more preferably no less than about 75% of the cavity resonant frequency (preferably the first order cavity resonant frequency) and most preferably no less than about 90% of the cavity resonant frequency (preferably the first order cavity resonant frequency), and preferably no more than about 90% of the cavity resonant frequency (preferably the first order cavity resonant frequency) but no preferably no more than about 135% of the cavity resonant frequency (preferably the first order cavity resonant frequency), more preferably no more than about 125% of the cavity resonant frequency (preferably the first order cavity resonant frequency) and most preferably no more than about 110% of the cavity resonant frequency (preferably the first order cavity resonant frequency).

For optimum tuning of the cavity resonant frequency, the dielectric capacitance of each varactor must be maintained within a specific range. Although the optimum value of the dielectric capacitance depends on the cavity geometry and the cavity resonant frequency, the minimum dielectric capacitance is preferably about 0.01 pf, more preferably about 0.05 pf, and most preferably about 0.10 pf, and the maximum dielectric capacitance is preferably about 50 pf, more preferably about 10 pf, and most preferably about 4 pf.

To realize these relatively low dielectric capacitance values, the area of metallization of the first and second tuning electrodes 128a and b is relatively small. The maximum area of metallization of each tuning electrode is preferably about 0.02 cm^2 and more preferably about 0.005 cm^2.

The thickness of the transmission line 78 is yet another important parameter to the performance of the

tuning device. Preferably, the minimum thickness of the transmission line 78 is about 3 and more preferably about 5 times the skin depth at the operating frequency for the selected conductive material in the transmission line. The maximum thickness of the transmission line is preferably about 0.5 mm and more preferably about 1.0 mm.

Yet other important parameters to tuning device performance are the thickness "T_s" of the substrate 98 and the electric permittivity of the substrate 98. Preferably, the thickness of the substrate 98 ranges from about 0.01 cm to about 0.1 cm and more preferably from about 0.02 to about 0.08 cm. The dielectric constant of the substrate 98 preferably is high enough so that the component 70 is physically small enough to fit into the cavity 54. The minimum dielectric constant of the substrate 98 is about 2 and more preferably about 9.

To reduce insertion losses due to coupling of the electromagnetic energy in the cavity 54 to the bias lines 106a,b, the bias lines 106a,b are connected to the transmission line 78 and ground plane 94 at voltage node 132 of the resonant circuit component 70. The voltage nod position 132 in the component 70 is at the center of the transmission line 78. The voltage node positions are calculated from the dielectric capacitance of the varactor, the characteristic impedance of the transmission line 78, and the resonant frequency. As will be appreciated, little, if any, electromagnetic energy will couple to the bias lines 106a,b when the bias lines 106a,b are connected at the voltage nodes.

To further reduce insertion losses due to coupling of the electromagnetic energy to the bias lines, a capacitor can be connected, preferably in series or in shunt, to one or both of the bias lines 106a,b. The shunt capacitor preferably has a maximum capacitance of about 100 pf and more preferably about 1,000 pf and a minimum capacitance of about 10 pf to about 50 pf. The shunt capacitor is preferably l cated at the point on the bias line which is

approximately a quarter of a wavelength (of the electromagnetic energy in the cavity 54) away from the voltage node 132 to which the bias line is connected. Alternatively, an inductor can be connected, in series or short, to one or both of the bias lines 106a,b. The induction is preferably located at the point on the bias line which is approximately one-half of a wavelength away from the voltage node 132 to which the bias line is connected.

The location of the resonant circuit component 70 within the cavity 54 depends upon the distribution of the electromagnetic field 74. The component 70 is preferably positioned at the area in the electromagnetic field 74 where the electric field component of the electromagnetic field 74 is at a maximum. Preferably, the component 70 is located on a surface (top or side surface) of the puck 66 or, if located away from the puck, within a distance of no more than about 10% of the width "W_p" of the puck 66.

Figures 7 and 8 respectively depict a second and third embodiments of a resonant circuit component. The transmission line 150a,b of the resonant circuit component 154 of Figure 7 is in a coplanar waveguide configuration while the transmission line 158a,b of the resonant circuit component 162 of Figure 8 is in a slot-line configuration. As noted above, the two sections of transmission line in each component are separated by a gap 166 and 170. The component 154 of Figure 7 can have a ground plane 174 located on the opposite side of the substrate 176 while the component of Figure 8 has no ground plane. Neither component has via holes. The component 162 of Figure 8 typically favors far field coupling to the electromagnetic energy in the cavity 54. The voltage nodes 178a-e in the components 154 and 162 of Figures 7 and 8 are located at the center of the transmission lines 150 and 158.

Figure 9 depicts a resonant circuit component 200 configured as an open-ended split resonator in microstrip line with the varactor 204 l ading the center gap 208

between the transmission lines 212a,b, all of which is supported by a substrate 216. A ground plane 220 is located on the bottom of the substrate 216. This component 200 differs from the components 70, 154, and 162 of Figures 3 and 7-8 in that the component 200 requires only one varactor 204. This structure can be large because each of the transmission lines 212a,b has a length that is at least one-half of the wavelength of the electromagnetic energy in the cavity 54.

Figure 10 depicts a resonant circuit component 240 configured as a short-ended split resonator in coplanar waveguide with the varactor 244 loading the center gap 248 between the transmission lines 254a,b, all of which is supported by a substrate 258. A DC isolation gap 262a,b is located on each side of the varactor-loaded gap 248 for biasing the varactor 244. A ground plane 266 can be located on the bottom of the substrate 258. To make the component 240 physically smaller, via holes (not shown) can be located at either end 270a,b of the component 240 to short circuit the transmission lines 254a,b to the ground plane 266. The bias lines 274a,b are each connected to a voltage node 278a,b located at the two shorted transmission lines 254a,b of the component 240.

As noted above, the resonant frequency of the resonant circuit component is controlled by changing the dielectric capacitance of the varactor. The tuning sensitivity of the component is defined as the percentage tuning of the resonant frequency for the tuner versus the percentage change in the dielectric capacitance. This tuning selectivity also reflects the amount of the electromagnetic energy stored in the transmission line(s) versus the electromagnetic energy stored in the varactors. For the components of Figures 3 and 7-8, the larger the dielectric capacitance is for the varactors, the better the tuning selectivity of the resonant circuit component is. With a large dielectric capacitance (i.e., about 10 pf), the tuning sensitivity ranges from about 0.1 to about 0.5. The

selection of the dielectric capacitance value manipulates the stored energies in the transmission line(s) and the varactor(s) to obtain a high Q for the component while maintaining a reasonably good tuning sensitivity. The minimum Q for the component is at least about 75, more preferably at least about 150 and most preferably at least about 250. For the components of Figures 9 and 10, the tuning sensitivity typically ranges from about 0.05 to about 0.18. There is a specific dielectric capacitance value required to realize the optimal sensitivity of about 0.18. Accordingly, the components of Figures 9 and 10 have lower tuning sensitivities than the components of Figures 3 and 7-8.

Figures 11 and 12 depict an embodiment of a distributed element resonant circuit component. The component 350 has a center conductor 354 and two coplanar ground planes 358 and 362 positioned on either side of the center conductor 354. The center conductor 354 and ground planes 358 and 362 are located above a thin or thick film dielectric material 366 which is deposited on an electrically insulating substrate 370. The dielectric material 366 is distributed over a substantial length "L_{DM}" of the substrate 370. This length "L_{DM}" can vary from about one-eighth of a wavelength to the length of the entire substrate 370. The distributed element component is fabricated by first depositing the dielectric material 366 on a suitable substrate 370, such as lanthanum aluminate, neodynium gallate, aluminum oxide, and magnesium oxide. The substrate 370 must support growth of a low-loss tunable dielectric material, be electrically insulating, and have low losses at the frequency of the electromagnetic energy in the cavity 54. A conductive layer is subsequently deposited and etched to form a resonant circuit with a first order resonance in the vicinity of the cavity resonant frequency. The cavity is tuned by altering the DC bias applied to the dielectric material via bias leads

attached to the planar conductors, thus altering the resonant frequency of the component.

A variety of other varactor configurations can be employed in the resonant circuit component. By way of example, Figures 13 and 14 depict a second embodiment of a lumped element varactor. The tuning electrodes 450a,b are located on a common surface 454 of the self-supporting bulk dielectric material 458. An advantage of this design is it can significantly lower the dielectric capacitance values of the varactor while maintaining high electric fields (and thus tunabilities) across the gap 462 between the tuning electrodes 450a,b. The gap 462 preferably ranges from about 30 to about 100 microns in width.

Figures 15 and 16 depict a third embodiment of a lumped element varactor according to the present invention. The varactor 500 has the tuning electrodes 504a,b deposited on a common surface 506 of a thick film dielectric material 508 which in turn is deposited on an electrically insulating, low electric permittivity substrate 512. The tuning electrodes 504a,b are separated by a gap 516. The substrate 512 preferably has an impedance greater than the impedance of the dielectric material 508. More preferably, the impedance of the substrate 512 is at least about 200% of the impedance of the dielectric material 508. The substrate 512 can be alumina (Al_2O_3) or magnesium oxide (MgO).

There are advantages to using a thick film dielectric material compared to a self-supporting bulk dielectric material. Because thick film dielectrics have a thickness (i.e., 1 to 6 mils) that is comparable to the width of the gap 516, fringing of the RF and DC electric fields into the portion of the bulk dielectric material furthest removed from the electrodes is minimized. Because the electric permittivity and thus the electrical susceptance of the thick film dielectric material is much larger than that of the substrate 512, the RF and DC electric fields are concentrated in the thick film dielectric material. For

certain frequencies and electromagnetic field strengths, this varactor 500 can therefore have enhanced tuning for a given DC voltage and lower overall capacitance values for the varactors.

The selection of a self-supporting bulk, thick film, and thin film dielectric material in the varactor depends upon the frequency of the electromagnetic energy in the cavity 54 and the electromagnetic field strength. Generally, for frequencies ranging from about 400 to about 800 MHz and/or RF power levels ranging from about 100 to about 1,000 Watts, it is preferable to use a self-supporting bulk dielectric material; for frequencies ranging from about 800 to about 2,000 MHz and/or RF power levels ranging from about 5 to about 100 Watts, it is preferable to use a thick film dielectric material; and finally for frequencies ranging from about 2,000 MHz to about 100 GHz and/or RF power levels ranging from about 0.1 to about 5 Watts, it is preferable to use a thin film dielectric material.

The varactor 550 of Figures 17 and 18 is identical to that of Figures 15 and 16 with the exception of an insulating dielectric thick film 554 located in the gap 516 between the tuning electrodes 504a,b and partially covering the electrodes 504a,b. The thick film 554 preferably has a voltage breakdown strength greater than that of air to reduce, compared to the varactor 500 of Figures 15 and 16, the possibility of voltage breakdown across the gap 516. The thick film 508 can be a material having a low electric permittivity and loss, such as alumina or magnesium oxide.

Figures 19 and 20 depict yet another embodiment of a varactor according to the present invention. The varactor 600 has a patterned tuning electrode 604 atop a thick film dielectric material 608. Another patterned tuning electrode 612 is located below the dielectric material 608. The electrodes and dielectric material are supported by an electrically insulating substrate 616. As will be appreciated, the tuning electrode 612 can be patterned as

shown or be a continuous layer covering the entire substrate. Because the dielectric capacitance is concentrated in the volume of the dielectric thick film 608 where the top and bottom electrodes overlap, the dielectric capacitance of this type of varactor can be extremely small (i.e., no more than about 2 pf), and the DC voltage required to tune the dielectric capacitance can kept to modest levels (i.e., no more than about 500 volts).

Figures 21 and 22 depict a further embodiment of a varactor 650 using a thin film dielectric material 654 in lieu of the thick film dielectric material 508 in the varactor 500 of Figures 16 and 17. The thin film dielectric material 654 has coplanar tuning electrodes 504a,b located on one side and an electrically insulating substrate 512 on the other.

The tuning process employed to yield a selected resonant frequency in the cavity 54 will now be described using the tuning system of Fig. 23. To initiate the tuning process, a selected resonant frequency is first transmitted to the control device 730 which selects a first electric field strength and communicates an appropriate control signal to the biasing source.

The biasing source supplies power to the biasing device which applies a first electric field of the first electric field strength to the dielectric substrate to produce a first mean electric permittivity in the dielectric material. The first mean electric permittivity causes a first cavity resonant frequency to be produced in the resonating cavity 54. The sensing device 724 measures the first cavity resonant frequency and generates a first signal. The control device 730 receives the first signal and generates a first control signal to the biasing source depending upon the difference between the selected resonant frequency and the first resonant frequency. By way of example, if the first resonant frequency is less than the selected resonant frequency, the first control signal will command the biasing source to apply more bias through the

biasing device. If the first r sonant frequency is more than the selected resonant frequency, the first control signal will command the biasing source to apply less bias through the biasing source.

When the biasing source responds to the first control signal, a second electric field of a second electric field strength is applied to the dielectric material to produce a second mean electric permittivity in the material. The second electric field strength is different from the first electric field strength. The sensing device 724 measures a second cavity resonant frequency that is different from the first cavity resonant frequency and communicates a second signal to the control device 730. The control device 730 communicates an appropriate second control signal to the biasing source which applies bias through the biasing source to produce a third electric field strength in the defined region of the dielectric material.

The above-described steps are repeated until the selected cavity resonant frequency is produced in the resonating cavity. Generally, the time required to produc the selected resonant frequency in the resonating cavity is no more than about $1x10^{-3}$ seconds and more generally ranges from about $1x10^{-7}$ to about $1x10^{-4}$ seconds. The time required to obtain a selected cavity resonant frequency is therefore several orders of magnitude less than the times required by existing tuning techniques.

In selecting an electric field strength, the control device 730 can compare the selected resonant frequency with a predetermined set of values for the resonant frequency which are indexed against a corresponding set of predetermined electric field strengths. The sets can be generated either experimentally or during the operational tuning of the resonating cavity. Where one or more selected resonant frequencies will be used regularly, the sets include the regularly used resonant frequencies and corresponding electric field strengths.

EXPERIMENT 1

To determine the impact of the unloaded Q of the resonant circuit component on cavity tuning and insertion loss, an experiment was conducted in which resonant circuit components having differing unloaded Q's were used to tune a dielectric resonating cavity. Figure 24 depicts cavity tuning (vertical axis) as a function of insertion loss ("IL") (horizontal axis) when the cavity is tuned using resonant circuit components with unloaded Q values (Q_o') varying from 100 to 500. "Cavity tuning" is defined as the change in cavity resonant frequency (as a result of tuning)/the initial cavity resonant frequency. The unloaded Q (Q_o) of the dielectric resonating cavity is 5,000; the initial cavity resonant frequency (f_o) is 900 MHz; the resonant frequency of the resonant circuit component (f_o') is tuned 2% (i.e., the resonant frequency is changed 2% from the initial resonant frequency); and the external Q (Q_e) (assuming the resonant circuit component is loss-free) is 707. Accordingly, cavity losses are assumed to be attributable primarily to loading by the external circuit. During the experiment, the resonant circuit component was placed in various positions in the cavity to provide differing mutual coupling coefficients between the component and the oscillating electromagnetic field in the cavity. With reference to Figure 24, maximum tuning with minimal cavity insertion loss is obtained by increasing the unloaded Q of the cavity resonant circuit component. At the lower end of each curve in Figure 24, the mutual coupling coefficient was relatively low and the insertion loss relatively low while at the upper end of each curve the mutual coupling coefficient was relatively high and the insertion loss was relatively high.

EXPERIMENT 2

To determine the impact of differing degrees of tuning of the resonant circuit component on cavity tuning and insertion loss, an experiment was conducted in which a resonant circuit component was inserted into a dielectric

resonating cavity and subjected to differing degrees of tuning ranging from 1 to 4%. The resonant circuit component had a constant Q_o' of 180. During the experiment, the resonant circuit component was placed in various positions in the cavity to provide differing mutual coupling coefficients between the component and the oscillating electromagnetic field in the cavity.

Figure 25 depicts cavity tuning (vertical axis) as a function of insertion loss (horizontal axis). As can be seen from Figure 25, increasing the range of frequencies over which the resonant circuit component is tun d increases the frequency range over which a cavity can be tuned for a given insertion loss. As can also be seen from Figure 25 and as mentioned above, the mutual coupling coefficient is directly related to the magnitude of the insertion loss.

EXPERIMENT 3

To determine the relationship between cavity-to-tuner sensitivity to tuner/cavity resonant frequency ratio, a simulation was conducted in which resonant circuit components having differing resonant frequencies were inserted in a dielectric resonating cavity. Figure 26 depicts the results of the simulation. Figure 26 plots cavity-to-tuner sensitivity (χ_{Ω}) (vertical axis) as a function of the tuner/cavity resonant frequency ratio (ω'_0/ω_0) (horizontal axis). With reference to Figure 26, M is the mutual coupling coefficient between the cavity and the resonant circuit component; L is the inductance of the cavity; and L_o is the inductance of the resonant circuit component. Based on Figure 26, the cavity-to-tuner sensitivity ratio is maximized by designing a resonant frequency of the resonant circuit component that is in close proximity to the cavity resonant frequency. The cavity-to-tuner sensitivity is also increased by increasing the cavity-to-tuner coupling $(M/(LL_o)^{0.5})$.

While various embodiments of the present invention have been described in detail, it is apparent that modifications and adaptations of those embodiments will occur to those skilled in the art. However, it is to be expressly understood that such modifications and adaptations are within the scope of the present invention, as set forth in the following claims.

What is claimed is:

1. A tunable electromagnetic resonating apparatus, comprising:

a resonating cavity means for resonating at a cavity resonant frequency in response to electromagnetic energy received by said resonating cavity means;

an input means for inputting electromagnetic energy into said resonating cavity means;

an output means for outputting electromagnetic energy from said resonating cavity means;

a dielectric material, located within said resonating cavity means, having an electric permittivity that is a function of a voltage applied thereto; and

biasing means for applying the variable voltage to said dielectric material, the biasing means establishing a dielectric capacitance across at least a portion of the dielectric material, wherein said cavity resonant frequency is altered by altering said electric permittivity and wherein said dielectric capacitance is no more than about 50 picofarads to control parasitic resonances from said electromagnetic energy.

2. The apparatus, as claimed in Claim 1, further comprising leakage control means for controlling an amount of the electromagnetic energy conducted by said biasing means.

3. The apparatus, as claimed in Claim 1, wherein said biasing means applies to said thin film dielectric material an electric field having an electric field strength ranging from about 0.05 to about 500 kv/cm.

4. The apparatus, as claimed in Claim 2, wherein:

said capacitance ranges from about 0.05 to about 25 picofarads.

5. The apparatus, as claimed in Claim 1, wherein:

said resonating cavity means includes a second dielectric material having a substantially constant permittivity during operation of said apparatus, said thin

film dielectric material being located in close proximity to said second dielectric material.

6. The apparatus, as claimed in Claim 1, wherein: said electromagnetic energy has a frequency ranging from about $4x10^6$ to about $1x10^{11}$ Hz.

7. The apparatus, as claimed in Claim 1, wherein: said dielectric material includes at least one of a ferroelectric and paraelectric material.

8. The apparatus, as claimed in Claim 7, wherein: said dielectric material is selected from the group consisting of $BaTiO_3$, $SrTiO_3$, $KTaO_3$ $KNbO_3$, $PbTiO_3$, $PbZrO_3$ and composites and mixtures thereof.

9. The apparatus, as claimed in Claim 1, wherein the dielectric material has a thickness of no more than about 500 microns and the cavity resonant frequency is no more than about $8x10^8$ Hz.

10. The apparatus, as claimed in Claim 1, wherein the dielectric material has a thickness ranging from about 5 to about 200 microns and the cavity resonant frequency ranges from about $8x10^8$ to about $2x10^9$ Hz.

11. The apparatus, as claimed in Claim 1, wherein the dielectric material has a thickness of at least about 0.1 microns and the cavity resonant frequency is at least about $2x10^9$ Hz.

12. The apparatus, as claimed in Claim 1, further comprising:

a second dielectric material positioned at a distance from said dielectric material located in said resonating cavity means, said second dielectric material having a second electric permittivity that is also altered to provide an increased range of tunable resonant frequencies in said resonating cavity means.

13. The apparatus, as claimed in Claim 1, wherein the biasing means comprises first and second electrodes supported by a substrate and separated by a gap, the gap containing at least a portion of the dielectric material and at least a portion of the substrate, such that the

first and second electrodes and the at least a portion of the dielectric material define a first path for electromagnetic energy and the first and second electrodes and the at least a portion of the substrate define a second path for electromagnetic energy wherein, when electromagnetic energy passes through the tuning device, a first portion of the electromagnetic energy follows the first path and a second portion of the electromagnetic energy follows the second path, with the first portion of the electromagnetic energy being larger than the second portion of the electromagnetic energy.

14. The apparatus, as claimed in Claim 1, further comprising:

leakage control means for controlling an amount of the electromagnetic energy conducted by said biasing means.

15. The apparatus, as claimed in Claim 13, further comprising:

an insulating material located in the gap and having a voltage breakdown strength that is more than the about 500 kv/cm.

16. In a tuning device located within a resonating cavity for altering a cavity resonant frequency of electromagnetic energy in the resonating cavity, said tuning device comprising:

a dielectric material having a dielectric impedance supported by a substrate having a substrate impedance, said thin film dielectric material having an electric permittivity that is a variable function of a voltage applied to said dielectric material; and

first and second electrodes supported by the substrate and separated by a gap for applying said voltage to said dielectric material, the gap containing at least a portion of the dielectric material and at least a portion of the substrate, such that the first and second electrodes and the at least a portion of the dielectric material define a first path for the electromagnetic energy and the first and second electrodes and the at least a portion of the

substrate define a second path for the electromagnetic energy wherein, when electromagnetic energy passes through the tuning device, a first portion of the electromagnetic energy follows the first path and a second portion of the electromagnetic energy follows the second path, with the first portion of the electromagnetic energy being larger than the second portion of the electromagnetic energy, whereby said resonant frequency is altered by altering said electric permittivity.

17. The tuning device, as claimed in Claim 16, wherein the dielectric impedance is less than the substrate impedance.

18. The tuning device, as claimed in Claim 16, wherein:

said dielectric material includes at least one of a ferroelectric and paraelectric material.

19. The tuning device, as claimed in Claim 16, wherein:

a capacitance across said at least a portion of the dielectric material is no more than about 10 picofarads.

20. The tuning device, as claimed in Claim 16, further comprising:

an insulating material located in the gap and having a voltage breakdown strength that is more than about 500 kv/cm.

21. The tuning device, as claimed in Claim 16, further comprising:

biasing means for applying the voltage to the dielectric material and

leakage control means for controlling an amount of the electromagnetic energy conducted by the biasing means.

22. The tuning device, as claimed in Claim 16, wherein said resonating cavity further comprises a dielectric puck and said dielectric material is supported by said puck.

23. The tuning device, as claimed in Claim 16, wherein said first and second paths are electrically connected in parallel.

24. A tunable electromagnetic resonating apparatus, comprising:

a resonating cavity means for resonating at a cavity resonant frequency in response to electromagnetic energy received by said resonating cavity means;

an input means for inputting electromagnetic energy into said resonating cavity means;

an output means for outputting electromagnetic energy from said resonating cavity means;

a dielectric material having an electric permittivity that is a variable function of a voltage applied to said dielectric material;

biasing means, in electrical contact with the dielectric material, for applying the voltage to the dielectric material; and

leakage control means for controlling an amount of the electromagnetic energy conducted by said biasing means, wherein the resonant frequency of the resonating cavity means is a variable function of the electric permittivity of the dielectric material.

25. The apparatus, as claimed in Claim 24, wherein the dielectric material is a bulk dielectric material.

26. The apparatus, as claimed in Claim 24, wherein said biasing means applies a capacitance across at least a portion of the dielectric material and the capacitance is no more than about 50 picofarads.

27. The apparatus, as claimed in Claim 24, wherein said biasing means comprises a conductor in electrical contact with the dielectric material and wherein said dielectric material is included in a circuit having a voltage node and wherein said leakage control means comprises a connection for the conductor positioned substantially at the voltage node.

28. The apparatus, as claimed in Claim 24, wherein said biasing means comprises a conductor in electrical contact with the dielectric material and wherein said leakage control means comprises at least one of a shunt capacitor and conductor connected to said conductor.

29. A method for altering a cavity resonant frequency of a resonating cavity, comprising the steps of:

applying a first electric field of a first electric field strength to a dielectric material positioned in a resonating cavity to produce a first electric permittivity in said dielectric material and a capacitance across the dielectric material that is no more than about 10 picofarads;

measuring a first resonant frequency of said resonating cavity;

selecting based on said first resonant frequency a second electric field strength that is sufficient to produce a selected resonant frequency in said resonating cavity.

30. The method, as claimed in Claim 29, wherein said selecting step comprises:

comparing said selected resonant frequency with a set of predetermined values for the resonant frequency of said resonating cavity and for the electric field strength corresponding thereto to select an electric field strength.

Fig. 1

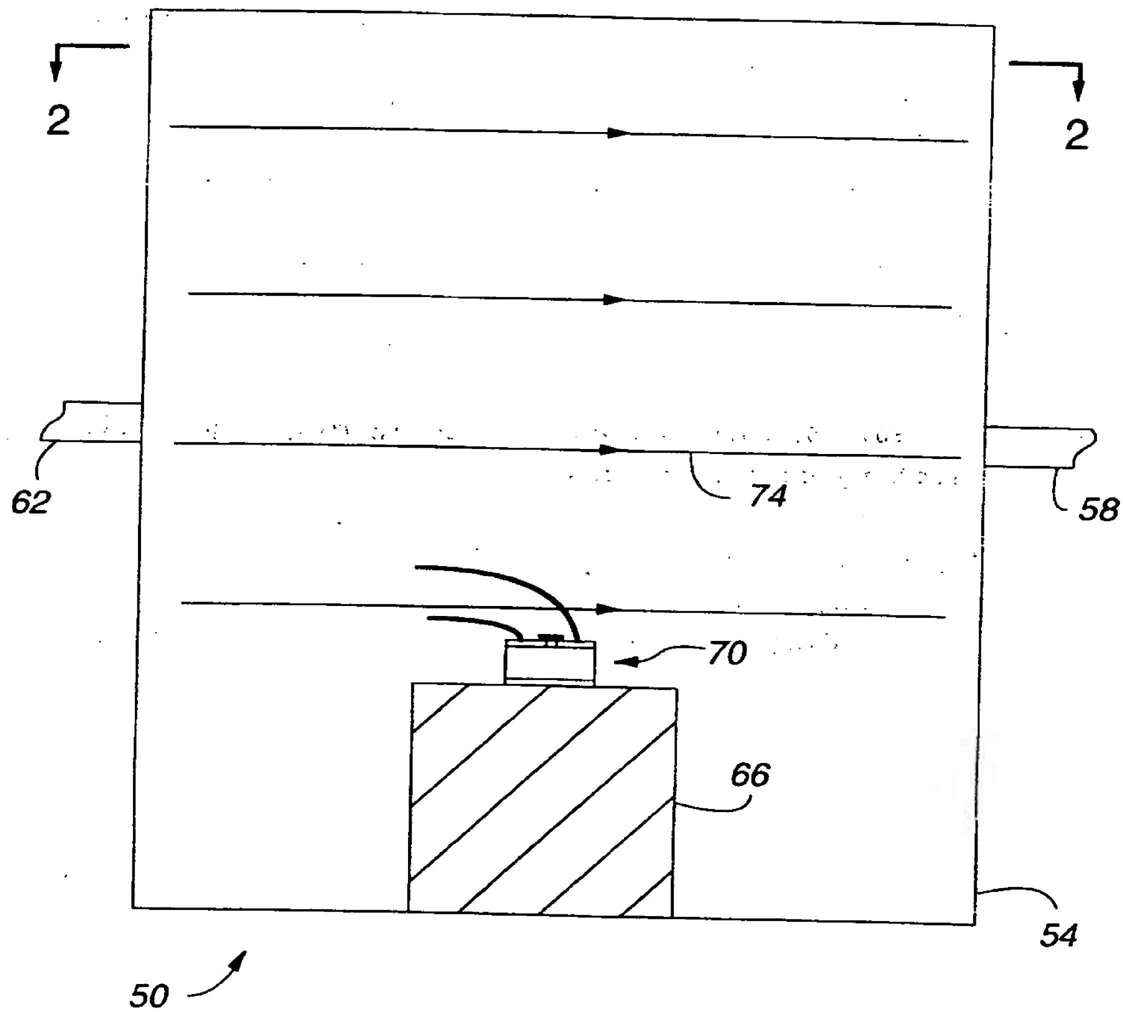


Fig. 2

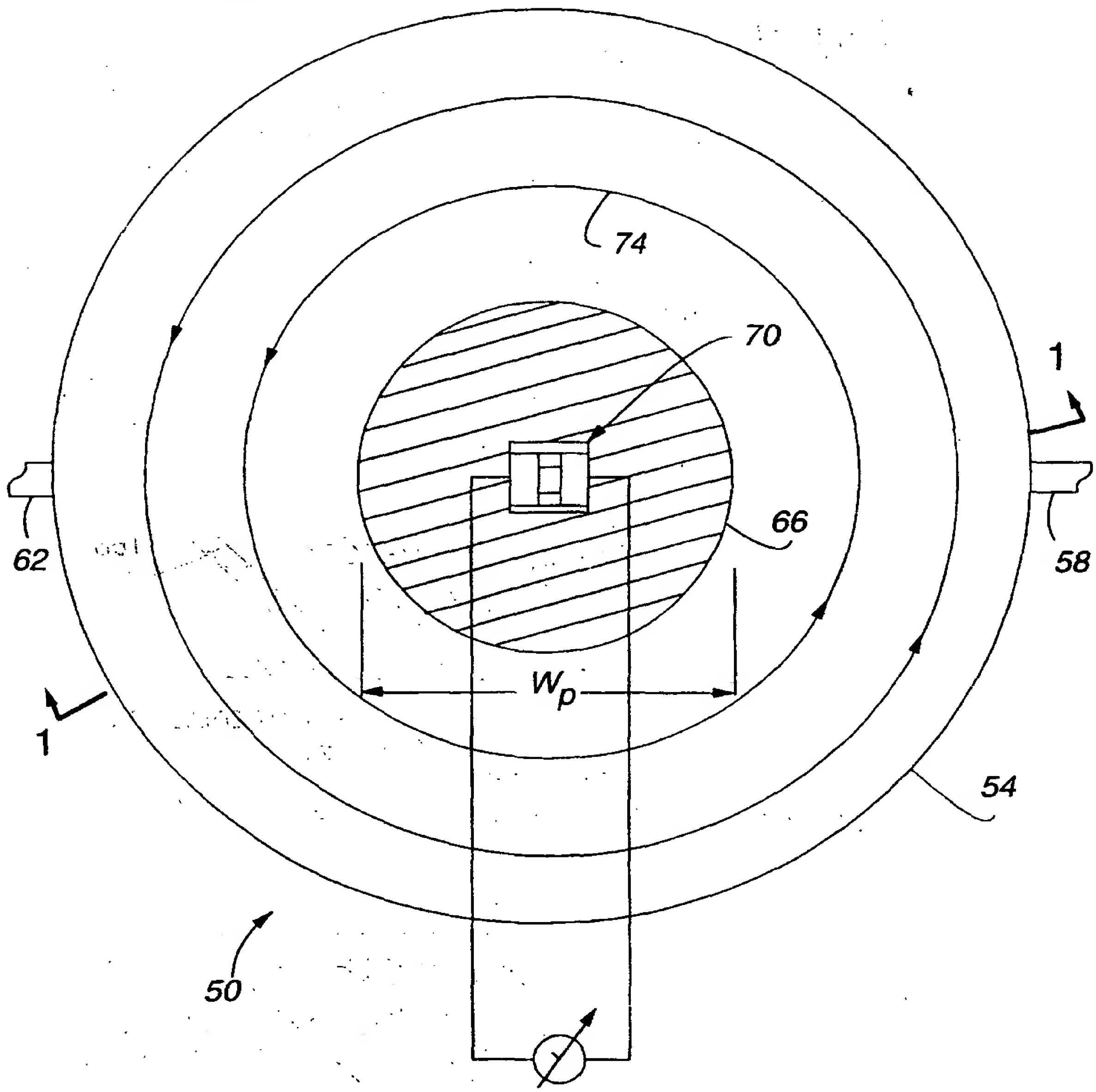


Fig. 3

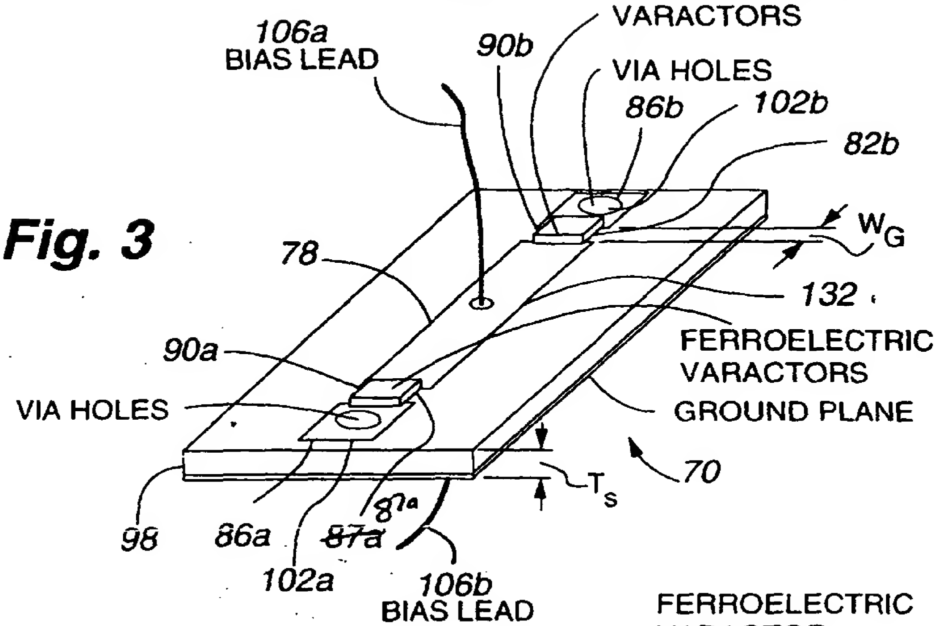


Fig. 7

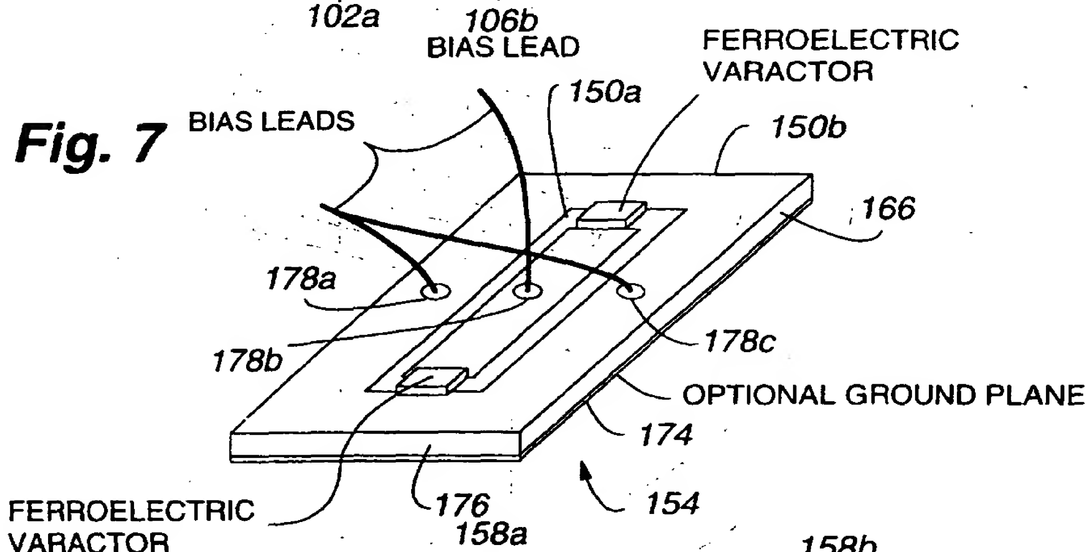


Fig. 8

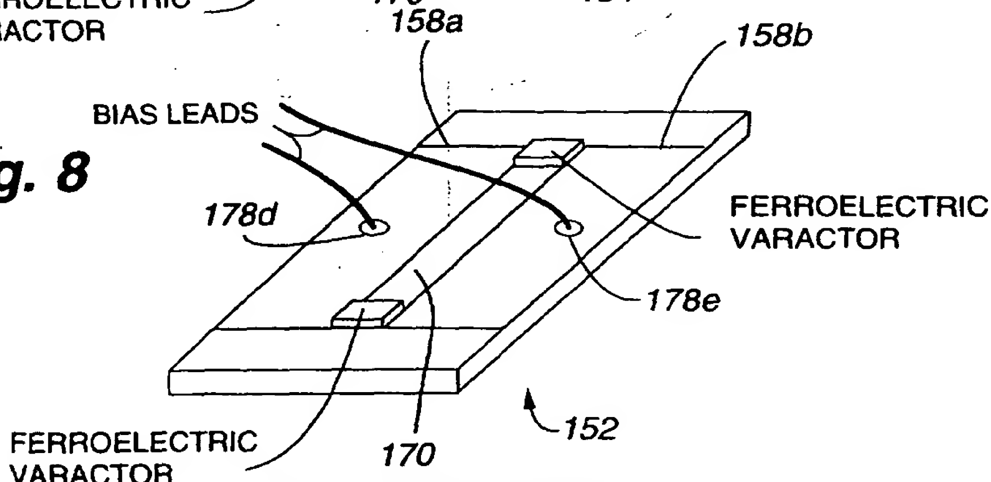
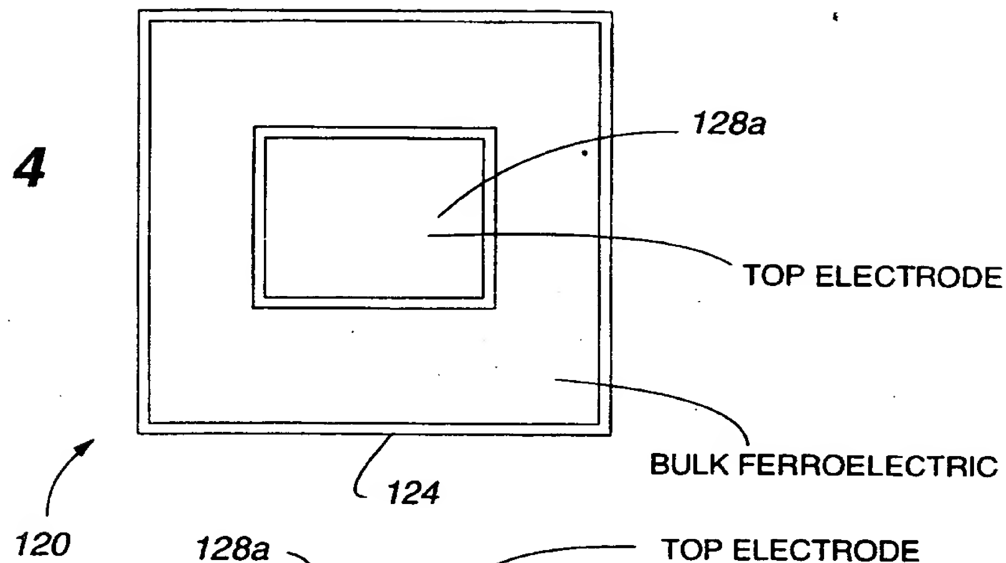


Fig. 4


128a
TOP ELECTRODE
BULK FERROELECTRIC
124
120

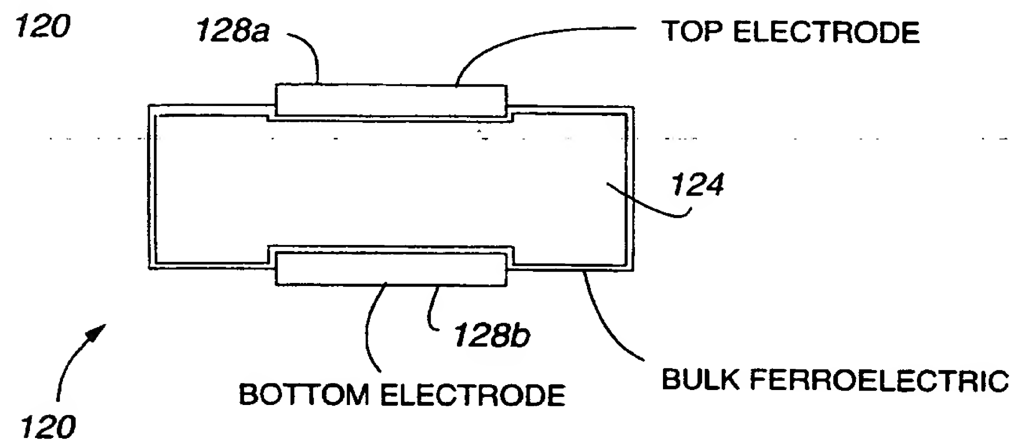

120
128a
TOP ELECTRODE
124
128b
BOTTOM ELECTRODE
BULK FERROELECTRIC
120

Fig. 5

Fig. 6

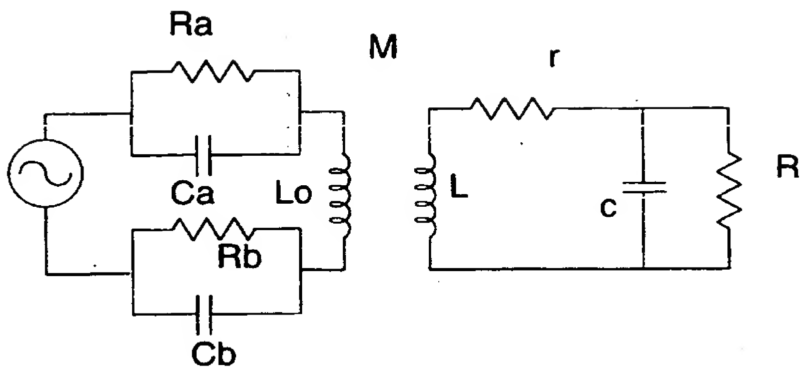


Fig. 9

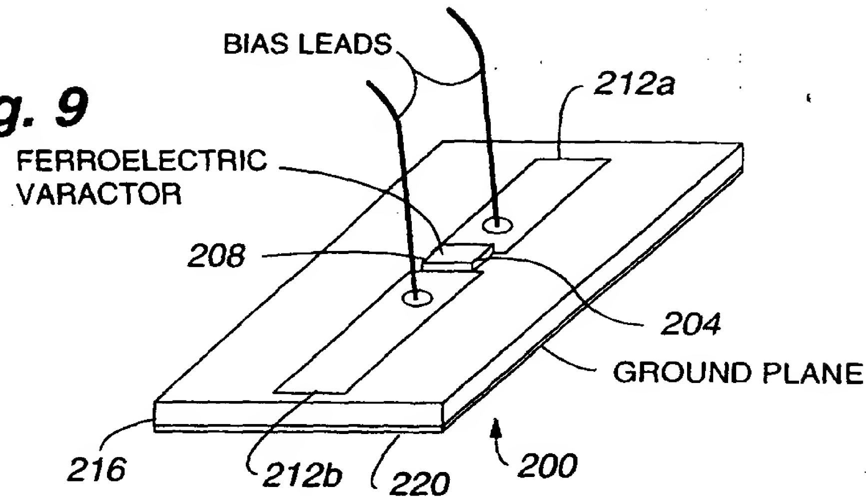
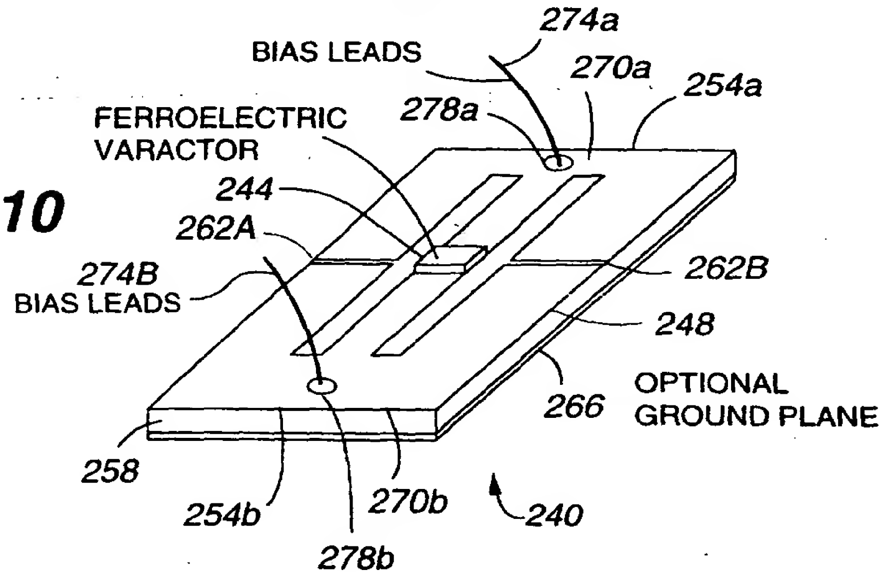

BIAS LEADS
212a
FERROELECTRIC VARACTOR
208
204
GROUND PLANE
216
212b
220
200

Fig. 10


274a
BIAS LEADS
270a
254a
278a
FERROELECTRIC VARACTOR
244
262A
274B
BIAS LEADS
262B
248
266
OPTIONAL GROUND PLANE
258
254b
270b
240
278b

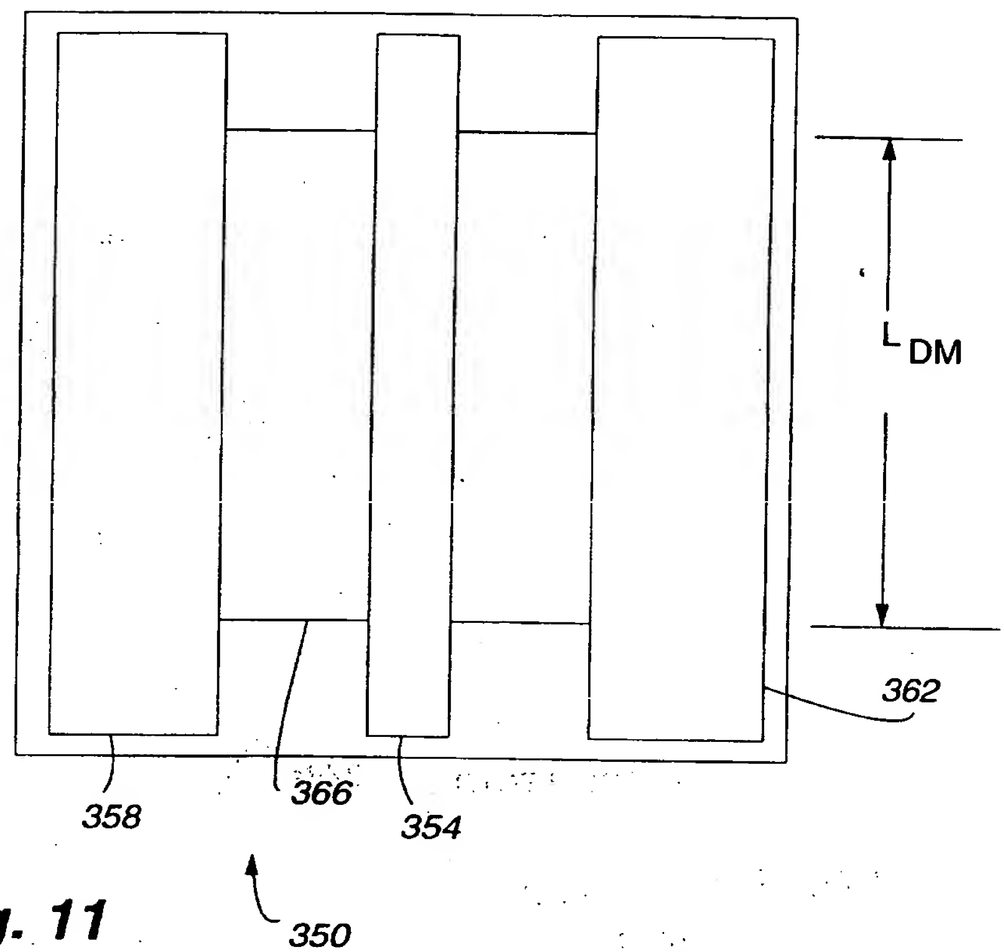
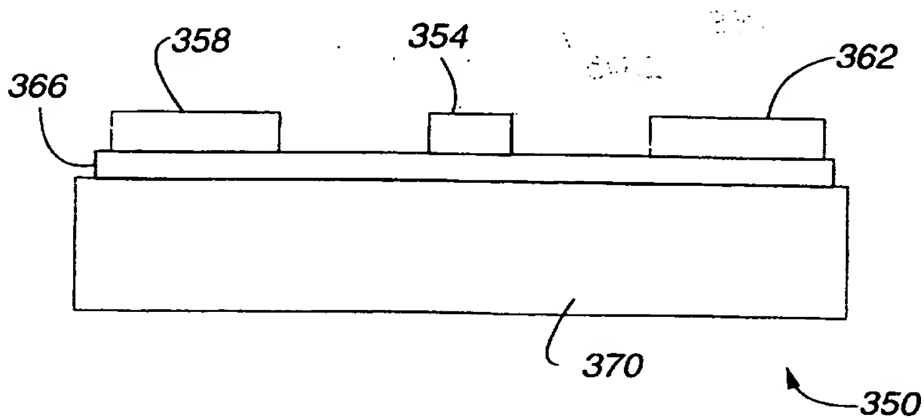


Fig. 11

Fig. 12



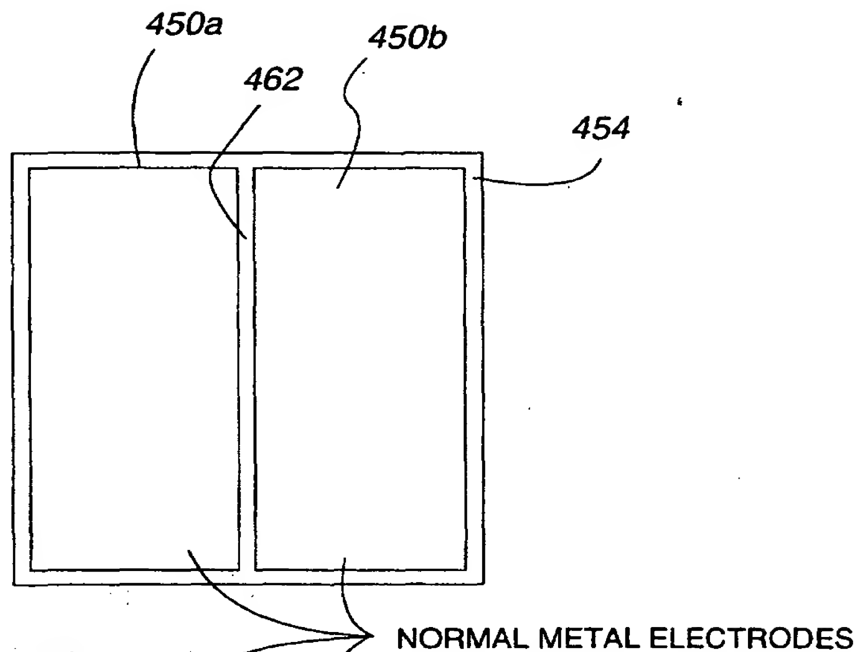

450a
462
450b
454
NORMAL METAL ELECTRODES

Fig. 13

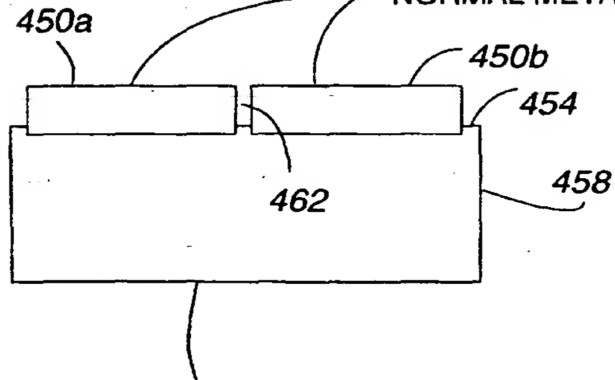

450a
450b
454
462
458
BULK FERROELECTRIC

Fig. 14

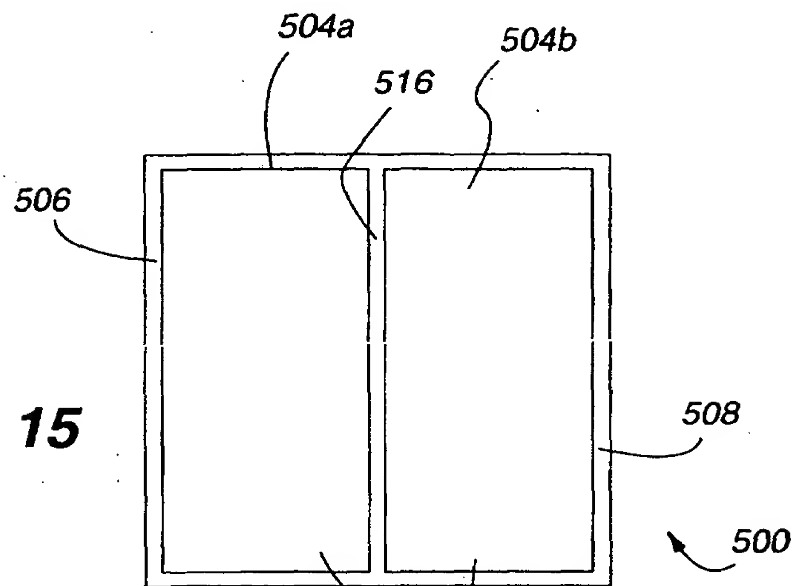

504a
504b
516
506
508
500

Fig. 15

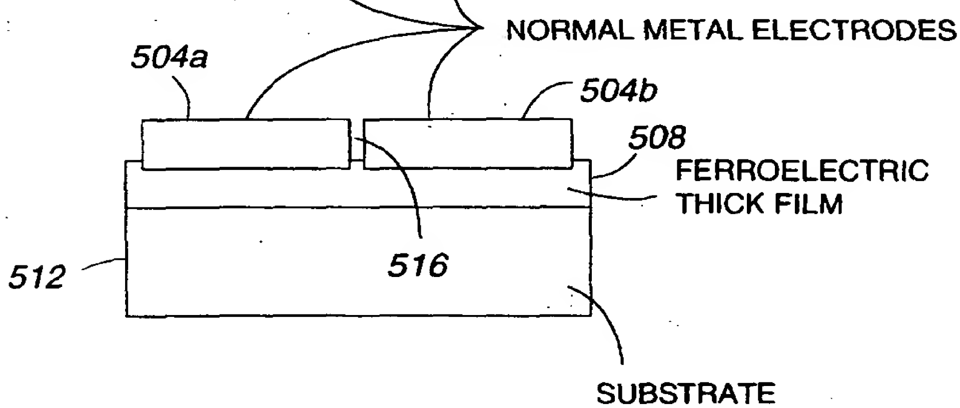

NORMAL METAL ELECTRODES
504a
504b
508
FERROELECTRIC
THICK FILM
512
516
SUBSTRATE

Fig. 16

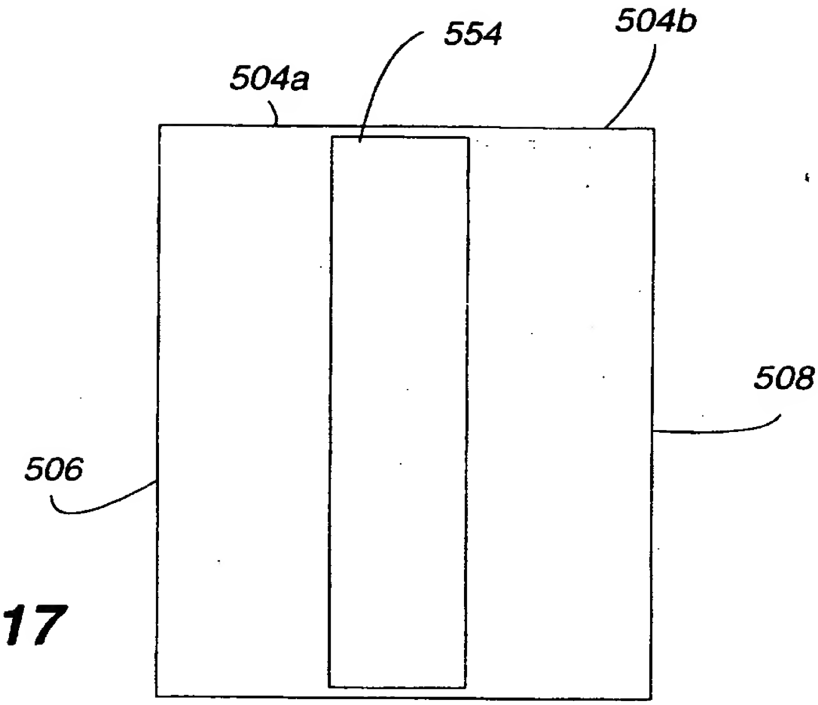


Fig. 17

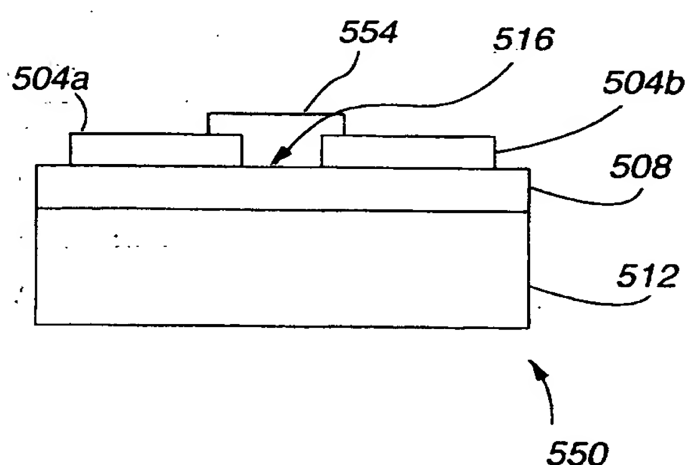


Fig. 18

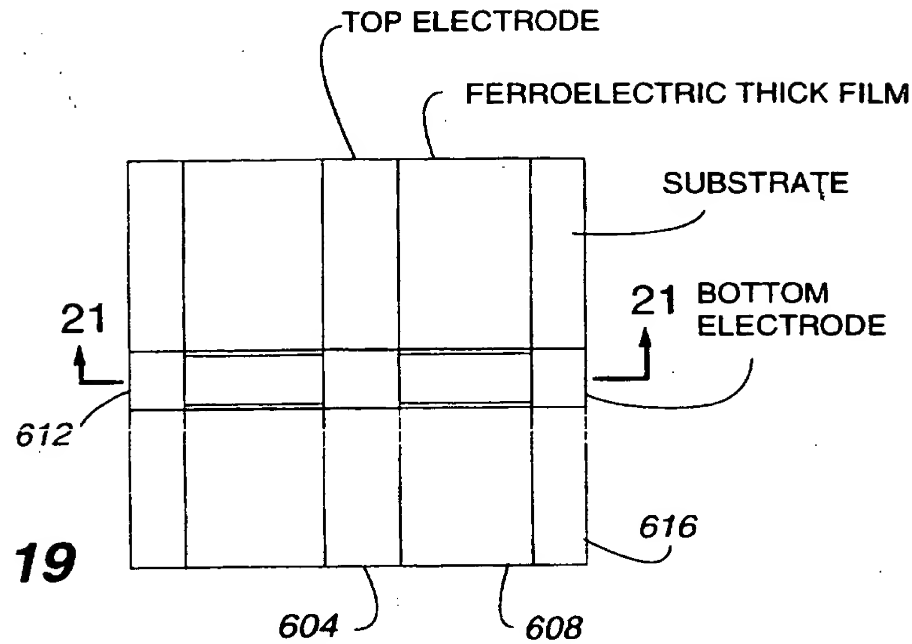

TOP ELECTRODE
FERROELECTRIC THICK FILM
SUBSTRATE
21
21
BOTTOM ELECTRODE
612
616
604
608

Fig. 19

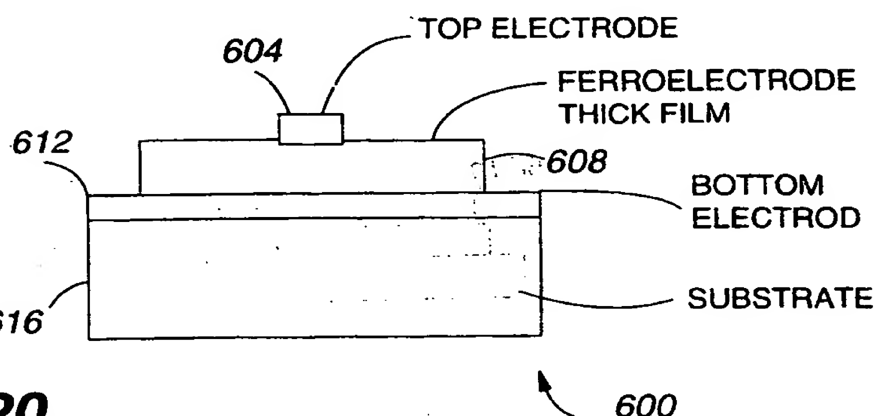

TOP ELECTRODE
604
FERROELECTRODE THICK FILM
612
608
BOTTOM ELECTROD
SUBSTRATE
616
600

Fig. 20

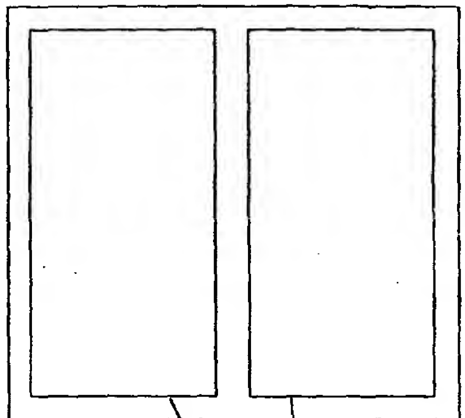


Fig. 21

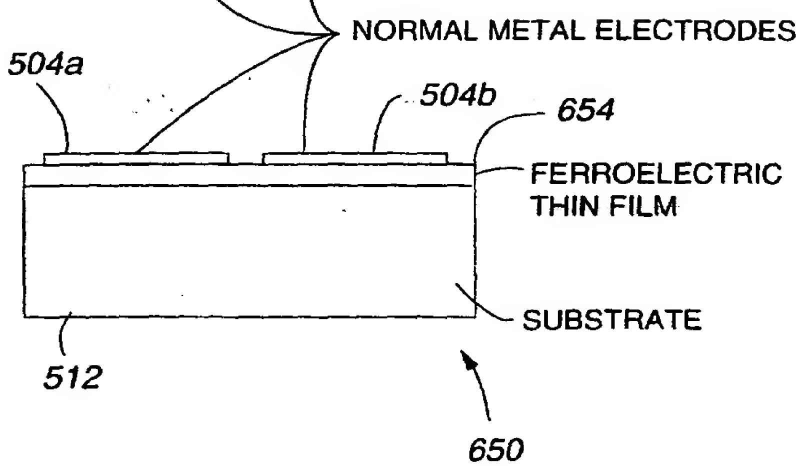

NORMAL METAL ELECTRODES
504a
504b
654
FERROELECTRIC
THIN FILM
SUBSTRATE
512
650

Fig. 22

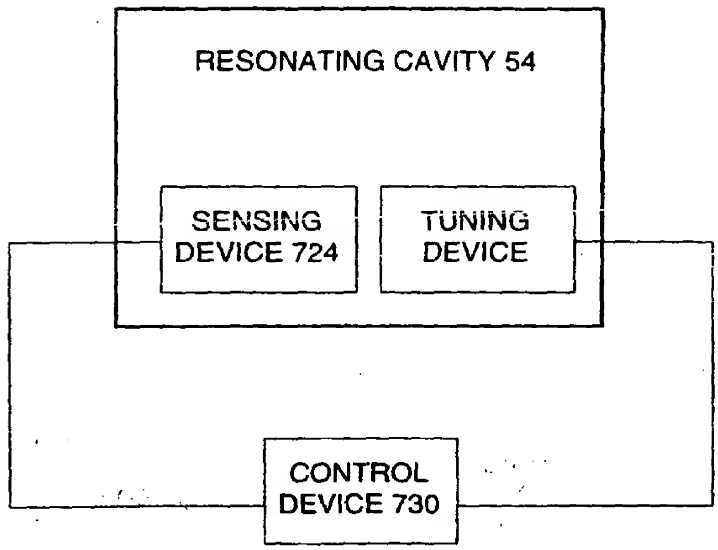

RESONATING CAVITY 54
SENSING DEVICE 724
TUNING DEVICE
CONTROL DEVICE 730

Fig. 23

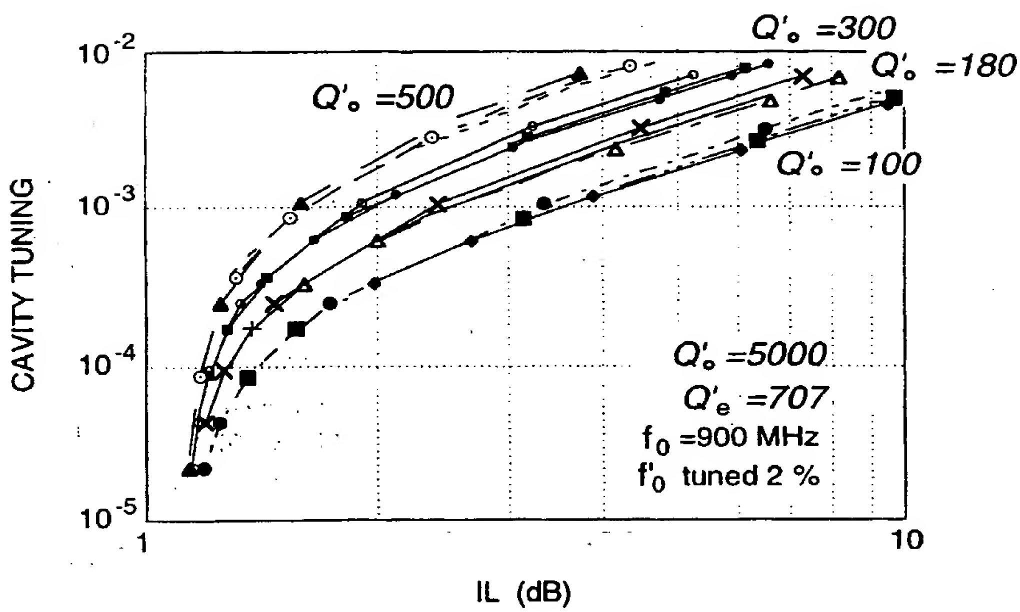

Q'o =300
Q'o =180
Q'o =500
Q'o =100
CAVITY TUNING
10^-2
10^-3
10^-4
10^-5
1
10
Q'o =5000
Q'e =707
f0 =900 MHz
f'0 tuned 2 %
IL (dB)

Fig. 24

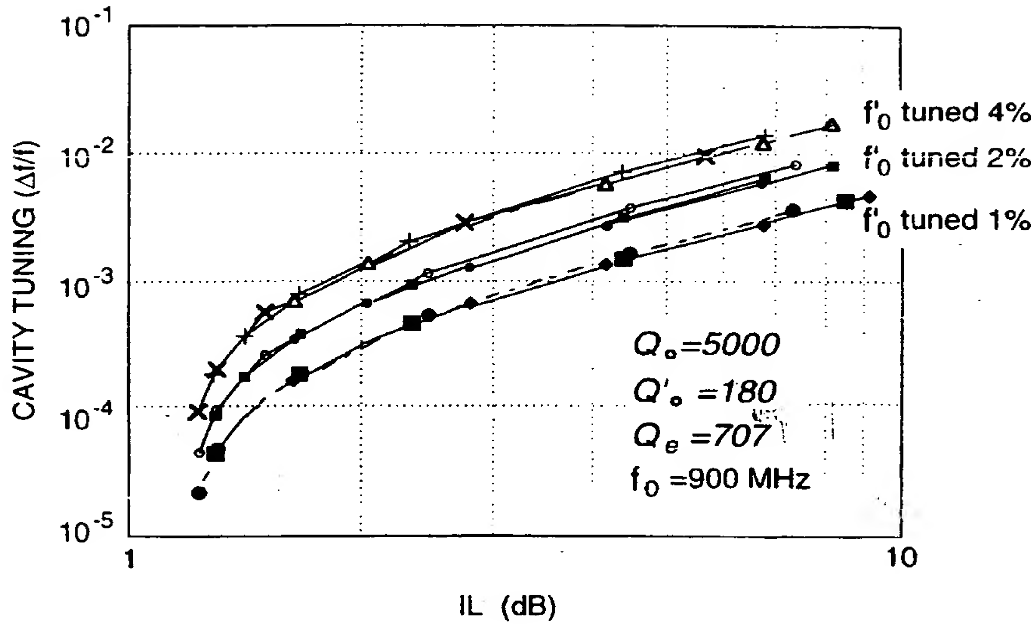

10^-1
10^-2
10^-3
10^-4
10^-5
CAVITY TUNING (Δf/f)
1
10
IL (dB)
f'0 tuned 4%
f'0 tuned 2%
f'0 tuned 1%
Qo=5000
Q'o =180
Qe =707
f0 =900 MHz

Fig. 25

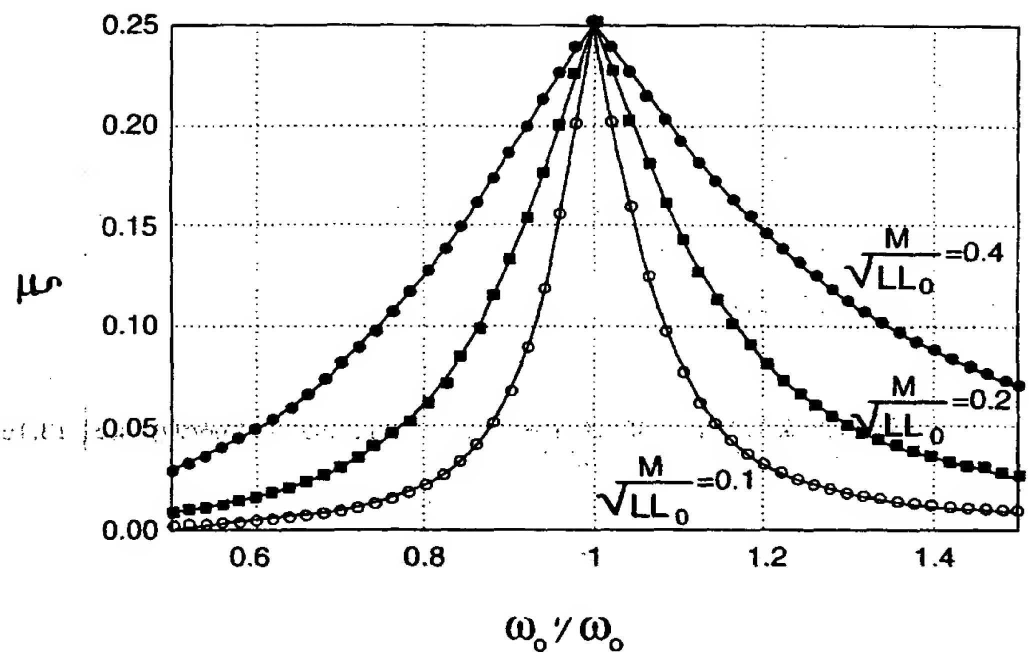

0.25
0.20
0.15
0.10
0.05
0.00
μ
0.6
0.8
1
1.2
1.4
ω₀'/ω₀
M/√LL₀ =0.4
M/√LL₀ =0.2
M/√LL₀ =0.1

Fig. 26

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/11164

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :H01P 7/06, 7/10; H01B 12/02
US CL :505/210, 700, 866; 333/99S, 219.1, 231, 235
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 505/210, 700, 701, 866; 333/99S, 202, 219.1, 227, 231, 235

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,459,123 A (DAS) 17 October 1995 (17/10/95), see entire document, especially figs. 1-3 and col 2, l. 62 - col 3, l. 38.	1-4,6-8,14,24-28
X, P -- Y	US 5,538,941 A (FINDIKOGLU ET AL) 23 July 1996 (23/07/96), see fig. 1A and col 3, l. 63 - col 4, l. 45.	1-11,14,15,24-28 -------- 13,16-23,29,30
Y, P	US 5,640,042 A (KOSCICA ET AL) 17 June 1997 (17/06/97), see fig. 1 and col 4, l. 43 - col 7, l. 23.	13,16-23,29,30

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
08 OCTOBER 1997	27 OCT 1997

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	BENNY LEE
Facsimile No. (703) 305-3230	Telephone No. (703) 308-4902

Form PCT/ISA/210 (second sheet)(July 1992)*